TM-71-1013-2

TECHNICAL MEMORANDUM

BERYLLIUM TECHNOLOGY

Bellcomm

BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W., WASHINGTON, D.C. 20024

COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Beryllium Technology

TM-71-1013-2

FILING CASE NO(S)- 237

DATE-February 9, 1971

AUTHOR(S)- C. C. Ong

FILING SUBJECT(S) (ASSIGNED BY AUTHOR(S))- Beryllium, Materials; Space Shuttle; Lightweight Structure

ABSTRACT

Beryllium is a structural material which has unusually high stiffness, unique thermal properties, and low weight. It is a good candidate material for structural elements which are buckling critical, deflection limited, require a high natural frequency, a high specific heat, or a high thermal conductivity. Its main drawbacks are brittleness, low strength and high cost. Moreover, only limited engineering experience with beryllium structure has been accumulated.

The brittleness of beryllium makes it difficult to work with. However, impressive progress in improving its ductility has been made recently, and current raw material products are considered manageable and easier to work with than are some of the advanced fiber reinforced composite materials. The material cost is high, but the overall cost of installed beryllium structure may be lower in some applications than equivalent ones made of advanced composites. The combined properties of high stiffness, low weight, high thermal conductivity and high temperature capability make beryllium competitive weightwise with other advanced materials.

The future of beryllium as a lightweight structural material appears to be overshadowed by the rapid development of advanced composites. However, since many design and fabrication difficulties still exist in the structural application of the latter, it is believed that, with some further development, beryllium could be used advantageously for many structural elements of the Space Shuttle. In view of the very limited beryllium research activity currently underway, expansion of beryllium technology to boost the soft areas of industry activities and to critically evaluate beryllium as a potential candidate material for Space Shuttle primary as well as secondary structures is recommended.

SEE REVERSE SIDE FOR DISTRIBUTION LIST

BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

SUBJECT: Beryllium Technology
Case 237

DATE: February 9, 1971

FROM: C. C. Ong

TM: 71-1013-2

TECHNICAL MEMORANDUM

1.0 INTRODUCTION[1,2]

Beryllium, a lightweight metal, was primarily used as a minor alloying addition to copper in the early 1930's. In the 1940's, it was found that the unique properties of beryllium such as low atomic weight and low neutron capture cross section made it a good moderator material in an atomic pile. Therefore, major interest in beryllium was expressed by the Atomic Energy Commission for applications in nuclear reactors, especially airborne nuclear reactors.

With successful manufacturing of fine grain beryllium block in the early 1950's the demand for beryllium as a structural material became significant. Serious interest in beryllium as an aerospace structural material began in the mid fifties because the high specific modulus (modulus to density ratio) of this material promised a great weight saving potential for certain structural components compared to engineering materials such as aluminum, titanium and stainless steel. Engineering applications of beryllium have been primarily restricted to non-structural items or secondary structures. Major programs using beryllium in limited structural applications include Polaris, C-5A, Poseidon, Nerva, and various nuclear weapons. Some of these programs have been either stopped abruptly or severely curtailed recently and the beryllium industry is currently facing an oversupply situation while at the same time experiencing a reduction in technology research activities. In addition, recent rapid progress on advanced fiber reinforced composite materials, which also exhibit high specific modulus, has forced a reevaluation of beryllium for structural purposes.

It was estimated that, in 1970, the beryllium industry of the U.S. produced about 600,000 pounds of hot pressed beryllium block and operated at about 30% of capacity. Current consumption of beryllium sheets was estimated to be only about 2000-4000 lbs/year.

The purpose of this memorandum is to review the status of beryllium technology and to assess its potential as a lightweight structural material. Emphasis is placed on its applicability to the Space Shuttle program.

2.0 PROPERTIES OF BERYLLIUM[1,3]

The attractive properties of beryllium which are the common reasons for its selection are:

1. Low density (0.066 lbs/in^3)
2. High modulus of elasticity (44 million psi)
3. High specific heat at normal and elevated temperature (0.40 BTU/LB/°F at room temperature)
4. Low specific heat at cryogenic temperature
5. Low neutron capture cross section
6. High melting point (2341°F)
7. High thermal conductivity (94 BTU/FT/HR/°F at room temperature)

There are also some unfavorable properties which cause great concern and limitations to the utilization of beryllium. They are:

1. Low fracture toughness
2. Low elongation limit at room temperature, particularly in the short transverse direction.
3. Low creep resistance
4. Strain rate sensitivity
5. Inability to produce ductile, high strength weld
6. Low strength (room temperature ultimate tensile strength of hot rolled sheet = 80,000 psi)

So far as structural applications are concerned the most important properties are its very high specific modulus, unique thermal properties and high temperature capability, low tensile strength and brittleness.

2.1 Specific Modulus

Among metallic materials commonly used in the aerospace industry only alloyed magnesium (0.066 lbs/in^3) approaches the low density of beryllium. Aluminum (0.101 lbs/in^3) is 50% heavier than beryllium, and titanium, steel and superalloys have a density ranging from two and a half to five times that of beryllium. While alloyed magnesium and aluminum are attractive on a density basis, these materials have moduli less than one-fourth the value of beryllium. The combination of high modulus and low density makes beryllium the material with highest modulus-to-density-ratio among all structural metals. Its specific modulus of 670×10^6 in. is more than six times those of aluminum, titanium and stainless steel and compares favorably with advanced composites as shown in Figure 1.[4]

2.2 High Temperature Capability and Other Thermal Properties

Both the stiffness and the strength of beryllium are largely retained up to a temperature of 1000°F. Beryllium sheet has been finish-rolled at 1400°F and probably will undergo permanent changes in properties when exposed to a temperature above this level for a considerable length of time. The room temperature specific heat is more than four times that of steel and twice that of aluminum. Beryllium also has a high thermal conductivity which helps to eliminate thermal gradients and protects the part against warpage and high thermal stresses. The combination of its thermal and mechanical properties at high temperatures makes beryllium an attractive high temperature structural and heat sink material.

2.3 Specific Strength

Although beryllium has a very high specific modulus its strength is only moderate as compared to other advanced materials. Figures 1 and 2 show that at room temperature beryllium compares favorably with aluminum, titanium and

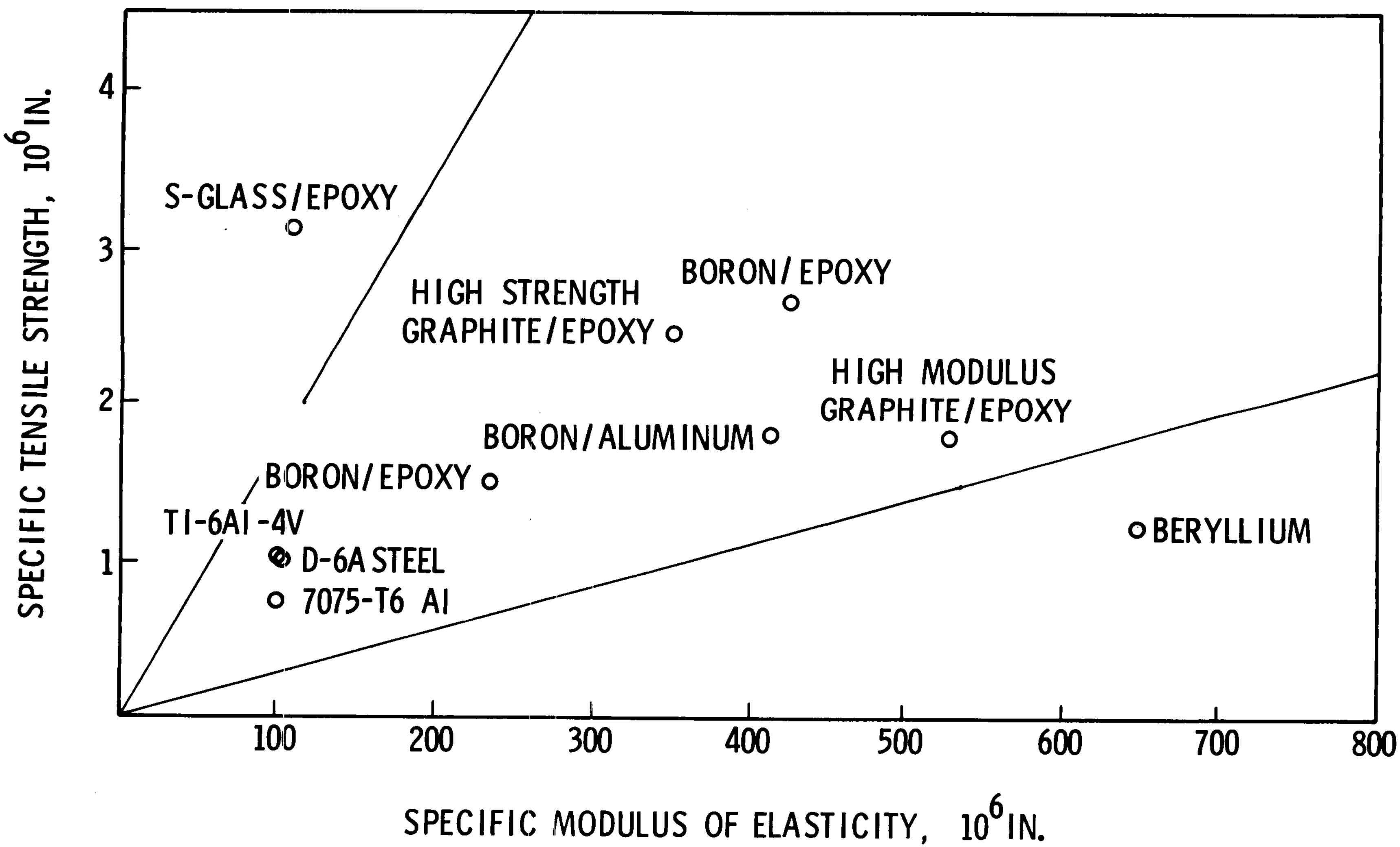


FIGURE 1-ROOM TEMPERATURE SPECIFIC PROPERTIES OF STRUCTURAL MATERIALS
(TAKEN FROM REFERENCE 4)

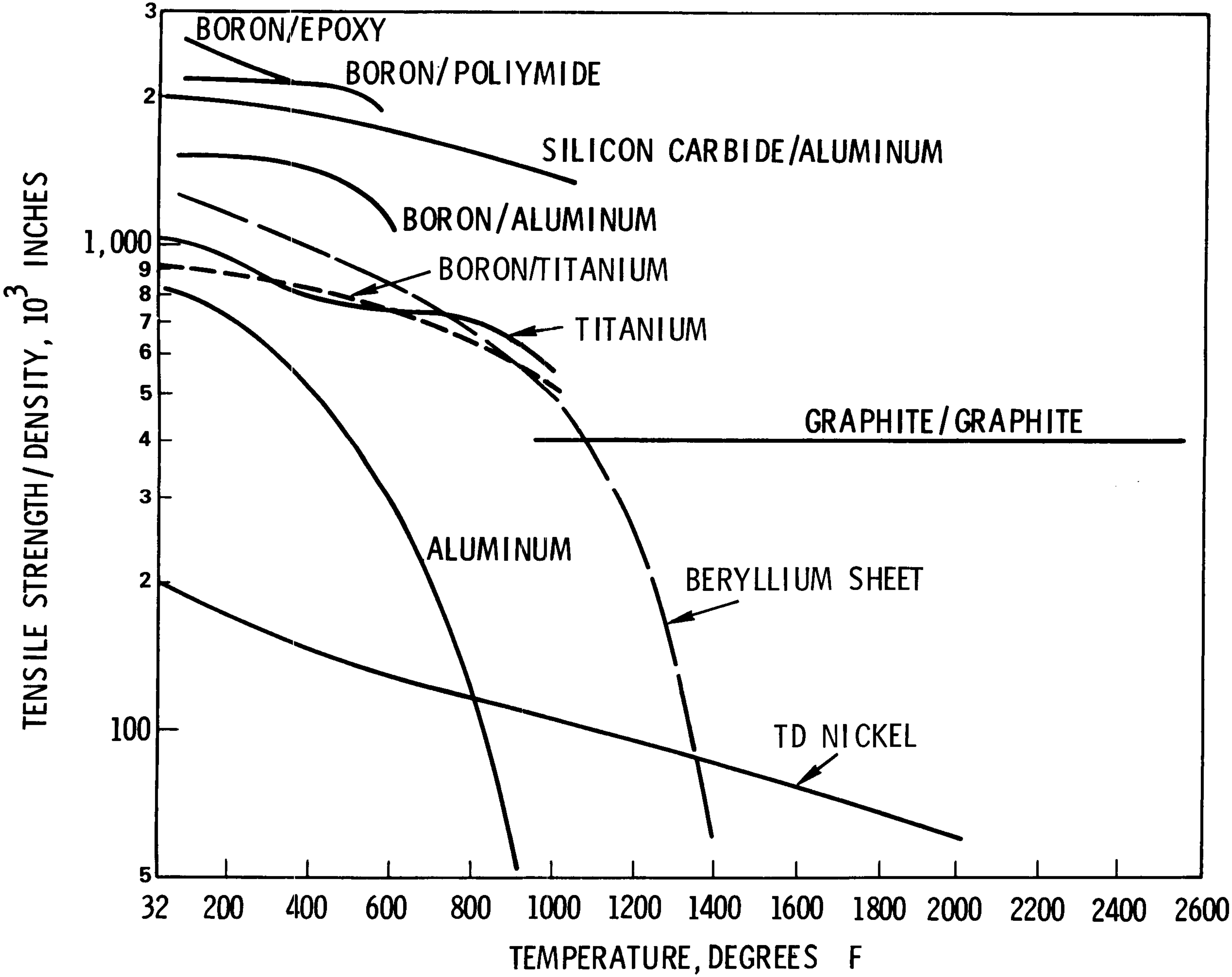


FIGURE 2 - SPECIFIC TENSILE STRENGTH VERSUS TEMPERATURE OF STRUCTURAL MATERIALS

stainless steel in specific strength, but advanced composites, such as boron/epoxy and graphite/epoxy have a much higher specific strength than beryllium. At elevated temperatures it is comparable to that of titanium. The strength limitation is one of the primary factors which prevent beryllium from extensive development and utilization at the scale of advanced composites.

2.4 Brittleness

The biggest barrier to a wide acceptance of beryllium in the aerospace industry has been its brittleness. This property is closely related to its low fracture toughness, low elongation limit, notch sensitivity and fabrication difficulties. At a temperature below 400°F formation of a crack could easily lead to a catastrophic crack propagation under service conditions. But the ductility undergoes a profound change around 400°F, and at about this temperature, beryllium can behave plastically.

It should be noted, however, that recent progress on beryllium metallurgy has made beryllium more ductile than ever before. According to Kawecki Berylco Industries, the current typical room temperature inplane elongation limit of beryllium sheet material is 15-17% and it is hopeful that a 20% elongation limit can be reached in the near future. Even at the present level, it is comparable to some of the aluminum and titanium alloys. However, the elongation limit along the short transverse direction is still small, about 0.5 to 1.0%. Therefore, beryllium is still a brittle material, but it is considered manageable in fabrication.

3.0 PRODUCT AVAILABILITY[1,3,5]

There are three major suppliers of beryllium in the United States. They are: The Brush Beryllium (Brush) Company, Kawecki Berylco Industries, Inc. (KBI), and General Astrometals (GA), a subsidiary of Anaconda.

Most of the beryllium oxide extracted from ore has been used for the production of beryllium copper alloys and to a lesser extent for beryllium-aluminum and ceramic production, Typically less than 25% of the basic beryllium oxide has been utilized to produce pure beryllium metals. Because copper, aluminum and other beryllium alloys do not appear to have significant potential as advanced structural materials, discussion will be limited to pure beryllium only.

A variety of pure beryllium products are available today. Most of these products have been produced from blocks or billets made by hot vacuum pressing techniques. The billets can be machined directly into structural shapes or made into commercial mill products by extrusion, rolling, or forging.

A new method developed recently is the hot isostatic pressing technique which permits the sintering and densification of beryllium powder to a shape very close to the final configuration of the structure. This method reduces the high cost of machining and material degradation, and may prove to be superior then earlier methods. However, the properties of the products made by this method have not yet been very well characterized.

3.1 Hot Pressed Block

Several grades of hot pressed beryllium are commercially available. Table I describes their types, typical uses and equivalent code numbers of three producers. The size of the pressings in the standard structural grades such as the Brush S-200, could be as large as 72" in diameter by 36" high, but they are usually limited to less than 40 inches in diameter. Blocks of high purity or high strength are usually available in smaller size than those of standard structural grade.

3.2 Semi-finished Machining Block

This product is the beryllium material most frequently purchased by the users. It is usually made from the hot pressed block according to users requirements.

3.3 Sheet, Plate and Foil

The flat products are usually rolled from standard structural grade blocks. The thicknesses and sizes available without special handling are listed in Table 2. With special orders, sheets as thick as 0.50 inches and as long as 200 inches can be produced. Foil as thin as 0.5 mil can also be made. Current specifications call for a minimum elongation limit of 10% and the typical thickness tolerance is ± 10%. The ultimate and yield strengths of sheet products have reached 80,000 psi and 60,000 psi, respectively.

TABLE 1

HOT PRESSED BLOCK GRADES

(Taken From Ref. 1)

GENERAL DESCRIPTION	SPECIFICATIONS			TYPICAL USES
	Brush	KBI	G.A.	
Very High Purity (99.6 to 99.8% Be)	---	---	SR	Research studies, alloying, special nuclear and instrumentation applications
High Purity (99% Be)	N-50	HP-8	CR	Nuclear applications
High Purity - Structural	S-100	HP-12	GB-1	Very few at present
Standard Structural	S-200-E	HP-20	GB-2	General purpose
Instrument Grade	I-400	HP-40	---	Instruments
High Strength - PEL	S-350	HP-41	---	High strength wrought products and instruments requiring ductility
High Strength - Structural	S-240	HP-21	---	Special weapons components
Brake Grade	BG-170	HP-10	---	Aircraft brakes and rocket thrust chambers

Past demand for beryllium sheet has never reached 40,000 pounds in any single year and the current consumption is believed to be far below that value.

TABLE 2

THIN FLAT PRODUCTS (TAKEN FROM REF. 1)

Product	Thickness (inches)	Size (inches)
Sheet	.020 - .249	36" to 48" wide x 65 to 120 depending upon gage
Plate	.250 - .600	40 wide x 35 to 65 depending upon gage
Foil	.001 - .004	8 x 15 KBI
	.001 - .004	4 x 4 Brush
	.005 - .010	20 x 60 KBI
	.005 - .010	5 x 12 Brush
	.010 - .020	20 x 60 Brush

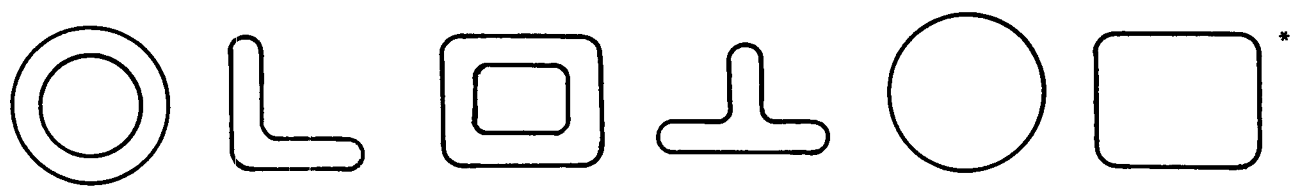
3.4 Extrusions and Forgings

Simple extruded shapes such as rod and heavy wall tube are readily producible. Some interesting structural shapes and thin wall tubes as shown in Table 3 have also been produced by extrusion.[6] The development of production processes is often troublesome and control of cross-sectional dimensions is difficult due to the fact that extrusion billets must be clad to prevent galling of beryllium on extrusion tools. Substantial developmental effort is needed before extruded structural members of beryllium, particularly thin wall tubes, becomes really practical from a production standpoint.

Forgings are in a comparable stage of development. At present beryllium forgings are limited to rather simple shapes. Forging is applied only to improve the properties at the expense of high cost. Typical mechanical properties of various beryllium products are compared in Table 4. It should be noted that these properties are under constant revision and improvement.

TABLE 3 - BERYLLIUM EXTRUSIONS
(TAKEN FROM REFERENCE 6)

WIDTH AND DEPTH OR DIAMETER	1/4" TO 8"	3/4" TO 3"	3/4" TO 3"	3/4" TO 3"	.100" MIN. TO 5 1/4" MAX.	2 1/2" TO 10" WIDE
THICKNESS	0.040 TO 0.750	0.060 TO 0.500	0.060 TO 0.500	0.060 TO 0.500		1/8" TO 1/2" THICK



* MAXIMUM GROSS SECTIONAL AREA AVAILABLE IS 20 SQUARE INCHES

TABLE 4

TYPICAL MECHANICAL PROPERTIES OF BERYLLIUM

(Taken From Ref. 3)

PRODUCT	ULTIMATE TENSILE STRENGTH, PSI	YIELD STRENGTH (0.2% OFF-SET), PSI	ELONGA-TION % IN 1 INCH
Hot Pressed Block	35-55,000	27-42,000	1-3
Sheet	70-100,000	50-70,000	5-15
Extrusions	70-95,000	35-60,000	3-12
Forgings	65-95,000	35,60,000	3-8
Wire	125-175,000		3-15

4.0 COST[1,6]

The high cost of beryllium raw materials and their fabrication has been generally considered one of the major drawbacks which prevent this material from extensive utilization in primary aerospace vehicle structures. However, substantial cost reduction has been achieved recently, particularly for sheet products and their fabrication which have enhanced the attractiveness of this material.

4.1 Hot Pressed Block

Current price for large pressing of structural grade blocks is \$50-70/lb. This price is volume sensitive. With a production volume over 100,000 pounds per month, the price can be expected to drop to about one-half of the current price.

4.2 Semi-finished Machining Block

The price of semi-finished machining block is sensitive to the characteristics of the product. A series of hollow truncated cones made from a 355 pound block have been priced recently at \$105/lb for a wall thickness of 1 inch and \$350/lb for a wall thickness of 1/4 inch. Future price reduction will depend upon the process improvement to be made, such as the ability to consolidate beryllium powder close to the shape of the finished product.

4.3 Sheet

The price of beryllium sheet at a production level of several hundred pounds per month was reported in early 1970 to range about \$700/lb for 0.020 inch sheet to \$230/lb for 0.120 inch sheet. It was estimated that the price could be reduced to about 1/3 of that level if the production were increased to 20,000 lbs per month as shown in Table 5.

According to KBI the price has been reduced substantially since early 1970 with the introduction of their new rolling facility. For example, 0.020 inch sheet is currently priced at \$465/lb and 0.12 inch sheet at \$130/lb as shown in Table 6. Officials of KBI also believe that with the recently improved fracture toughness characteristics of beryllium alloys, fabrication cost should be reduced considerably. For certain applications, the total installed cost of beryllium sheet could be as low as \$300/lb instead of \$1000/lb with fabrication cost amounting to slightly more than one-half of the total.

TABLE 5

ESTIMATED SHEET PRICES IN DOLLARS PER POUND AT PROJECTED VOLUMES IN POUNDS PER MONTH

(Taken From Ref. 1)

	Pounds Per Month			
	(1970)	(Projected)		
	600	4,000	10,000	20,000
Sheet Thickness	Dollars Per Pound			
.020	700	350	240	200
.040	410	215	160	135
.070	325	150	110	100
.120	230	120	90	75

TABLE 6 - PRICE LIST OF BERYLLIUM SHEET – GRADE PS-20 (KAWECKI BERYLCO INDUSTRIES, INC., AUGUST 1, 1970)

BASE PRICE – DOLLARS PER POUND*

STANDARD SIZE PIECE	NOMINAL THICKNESS–INCHES	SQUARE INCHES PER PIECE			GREATER THAN STANDARD	
		Under 200	200 to 1199	1200 to 3456	Width Extra	Length Extra
30″ x 84″	Including 0.020 to under 0.026″	$760.00	$620.00	$465.00	$100.00	$55.00
	″ 0.026 ″	550.00	450.00	350.00	100.00	55.00
36″ x 96″	″ 0.031″ ″ 0.041″	410.00	375.00	325.00	80.00	55.00
	″ 0.041″ ″ 0.051	350.00	300.00	275.00	80.00	40.00
	″ 0.051″ ″ 0.061″	270.00	220.00	200.00	60.00	35.00
	″ 0.061″ ″ 0.071″	270.00	220.00	200.00	60.00	30.00
	″ 0.071″ ″ 0.081″	236.25	192.50	175.00	50.00	22.00
	″ 0.081″ ″ 0.091″	236.25	192.50	175.00	50.00	22.00
	″ 0.091″ ″ 0.101″	202.50	165.00	150.00	45.00	20.00
	″ 0.101″ ″ 0.126″	175.50	143.00	130.00	45.00	15.00
30″ x 84″	″ 0.126″ ″ 0.151″	175.50	143.00	130.00	40.00	15.00
	″ 0.151″ ″ 0.176″	175.50	143.00	130.00	35.00	15.00
	″ 0.176″ ″ 0.201″	168.75	137.50	125.00	35.00	15.00
	″ 0.201″ ″ 0.226″	168.75	137.50	125.00	20.00	15.00
30″ x 66″	″ 0.226″ ″ 0.250″	162.00	132.00	120.00	20.00	12.50

*QUANTITY ADJUSTMENTS

TOTAL POUNDS	EXTRA +
1000 lbs. & over	BASE PRICE
500 to 999	+ 5%
250 to 499	+ 10%
100 to 249	+ 15%
25 to 99	+ 20%
Under 25	+ 25%

5.0 FABRICATION

Beryllium is not forgiving, and the fabricator has to understand the exact process required for its fabrication. Extraordinary control with respect to machining operations has to be exercised to insure a structurally sound product. Because of the toxic nature of beryllium powder, special precautions must be instituted to prevent air contamination. Despite these drawbacks beryllium is, however, manageable in fabrication and recent improvement on material ductility has placed beryllium in a relatively better position for fabrication than other advanced materials such as advanced composites.

5.1 Machining[7]

The important problems encountered in machining of beryllium are as follows:

1. Toxicity:

   Beryllium and its components are considered to be toxic, and skin reaction and a respiratory illness called berylliosis may develop upon exposure to it. Careful control of beryllium powder during fabrication is necessary to eliminate this danger. A limit of average inplant atmospheric concentration of beryllium to two micrograms per cubic meter in an 8-hour working day was recommended by the Atomic Energy Commission. It is noted that very few cases of berylliosis have been reported in recent years.

2. Twining:

   Twining, a rearrangement of some atoms to become mirror images of the others, and microcracking could be induced on the material surface by certain machining operations on beryllium. These defects can subsequently cause premature failure when the structure is subjected to high load. Past experience indicated that these effects can be minimized by using electrical discharge machining, electrochemical machining, and by control of cutting depth followed by chemical milling of the surface.

3. Chipout and Spalling:

The brittle beryllium is prone to chipout, cracking and spalling for which various control methods have been developed. Perhaps the most difficult fabrication problem of beryllium is to drill defect-free holes. The basic problems here are delamination spalling, and development of radial and circumferential fractures. Although several techniques have been developed to solve these problems, hole drilling remains a costly process.

5.2 Joining[8,9,10]

The feasibility of mechanical fastening, riveting, welding, brazing, adhesive bonding and diffusion bonding have all been demonstrated for joining beryllium structures. However, a satisfactory technique to produce ductile, high strength welds is yet to be developed. Currently, brazing and adhesive bonding seems to be the most appropriate joining technique with moderate temperature capability and diffusion bonding appears to have a potential for high temperature applications.

Brazing technology for beryllium is well developed. For low temperature service zinc brazing (brazing temperature 800°-850°F) has been successfully used. As the service temperature increases aluminum base brazing (1080°-1250°F), silver copper base brazing (1200-1660°F) or silver brazing (1620°-1700°F) should be applied. Since beryllium begins to recrystallize around 1450° to 1900°F, it is desirable to keep the brazing temperature below this range.

Bonding has also been used successfully. Epoxy-phenonic adhesive can provide good room temperature shear strength and retain a portion of it at temperatures up to 600°F. Past experience on brazing and adhesive bonding has been limited largely to moderate temperature (below 500°F) applications.

Riveting appears more effective for high temperature applications. The primary objection to riveting is the high stress concentration factor around a hole at low temperatures caused by the brittleness of beryllium. However, a combination of adhesive bonding and riveting has been used successfully. At low temperatures the adhesive bond carries the full load. As the temperature increases the ductility of beryllium also increases and the rivets begin to pick up the load.

Diffusion bonding for beryllium is currently being developed by North American Rockwell. Preliminary compression tests revealed excellent load capability and joint integrity. This joining technique is considered to be a promising one.

5.3 Forming[11]

Beryllium products can be formed into many complex configurations. The optimum forming temperature used to be around 1350°F for a variety of configurations such as straight bend, curved channels, hemispherical segments, and semicylinder with spherical ends. Recent improvement in material ductility has greatly facilitated the forming of beryllium elements. Current products permit forming at temperatures as much as 500°F below the above mentioned forming temperature. A minimum acceptable bend radius of 5 times its thickness has been established for cross-rolled beryllium sheet.

6.0 ENGINEERING EXPERIENCE

Application of beryllium has gone through several stages of different emphasis. It was primarily used in the nuclear industry between 1950 to 1960, and an increasing application in reentry vehicles and instruments was experienced in 1960 to 1965. Since 1965 applications such as aircraft brakes and rocket nozzles have been emerging. Limited structural components of beryllium have been used or experimentally applied to such aerospace vehicles as Polaris, Poseidon, Agena, Minuteman, Mercury, Gemini, TACSAT, C-5A and F4-C. The principal uses of beryllium in recent years and their distribution in terms of sales of the beryllium industry are as follows:[1]

Application	Approximate % Sales
Reentry Vehicles	45
Inertial Guidance & Instrumentation	20
Nuclear	15
Aircraft Structures and Systems (Brakes)	13
Missiles & Spacecraft Structures	2
Space Optics	4.5
Propulsion	0.5

Numerous research and development as well as application programs of beryllium have been conducted in the past 10 years. A number of structural application programs which may serve to illustrate the applicability of beryllium to the space shuttle program are briefly reviewed here.

6.1 Agena Spacecraft Forward Equipment Section[12,13]

Skin panels made of cross-rolled beryllium sheet were used to replace magnesium alloy on the Lockheed Agena D forward equipment section which is a right cylinder 60 inches in diameter and 40 inches in height. This was a structural redesign which led to a significant weight reduction. The basic panel is 0.050 inches thick with thickened edges formed by chemical milling. The panel attachment design was a simple lap joint using titanium screws in combination with the thickened edge. The first Agena carrying a beryllium skinned forward equipment section was successfully launched in June 1964. Later, about 3500 beryllium panels used in 168 Agena spacecraft were made in seven years of continuous production.

6.2 The Minuteman Beryllium Spacer[14]

The design and fabrication of a beryllium spacer serving as the interstage section between the reentry vehicle and the guidance and control section of the Minuteman booster was initiated in 1962 at AVCO. The spacer, about 32 inches in diameter and 12.5 inches long was a direct substitution for an existing aluminum-heat shield composite structure. It was made from a stress relieved ring-rolled forging having a shell thickness of 0.080 inches which was required for heat absorption during ascent without a heat shield. Four beryllium longerons located 90° apart were riveted and bonded to the shell structure. There were also five cut-outs in the basic shell structure. The beryllium structure weighed 10.2 lbs against 25 lbs of the original aluminum shell and was about 30.5% the weight of the combined aluminum shell and its heat shield.

6.3 Brake Disks of C-5A Aircraft[15,16]

Beryllium has a specific heat and a thermal conductivity more than four times those of steel, a low density about one-fourth that of steel and a high usable temperature range. For the same temperature rise, a steel heat sink would weight four times as much as the beryllium heat sink. Therefore, beryllium is an attractive material to replace the traditional steel for aircraft disk brakes.

Brush Beryllium Company developed in 1965 an aircraft brake grade beryllium specifically to fulfill the requirement of full circle brake disks acting as a structural member as well as a heat sink. In 1968, B. F. Goodrich qualified a brake using this material for the Lockheed/Air Force C-5A airplane. The disks were a full circle design with mechanically attached friction pads. Each C-5A requires 840 lbs of beryllium and by using beryllium, 1400 lbs was saved for each airplane.

6.4 Satellite Structural Assemblies[17]

The TACSAT I Satellite designed by Hughes Aircraft Company and successfully launched in 1967 had three beryllium structural items: the bearing and power transfer assembly (BAPTA), the UHF helix antenna tubes, and the bicone antenna mast. The primary reason for selecting beryllium was to meet the high stiffness requirement of the satellite with low weight structures.

Hughes Aircraft was also involved in producing a satellite wherein the adapter cone, spinning arms, despin platform and the BAPTA housing are all made of beryllium. Fabrication difficulties experienced included surface cleaning, structural adhesion and cracks on the sheet surface. These problems were solved in the fabrication development process. Weight savings up to 45% as compared to equivalent aluminum structures were experienced for some structural components.

6.5 Stiffener Straps for F-14 Aircraft[18]

Beryllium stiffener straps are being used by Grumman Aerospace Corporation in the radome supporting bulkhead of the navy fighter F-14. There are six stiffeners in each aircraft. The stiffeners are 5/8 inch wide, 0.162 inch thick and from 15 to 19 inches long. They are attached to the bulkhead by riveting. In order to reduce the structural weight, Grumman plans to use more beryllium in later models of the F-14.

6.6 Beryllium Structure Experience of McDonnell Douglas Corporation[19]

A number of aerospace companies have engineering experience with beryllium structures. Some of the programs conducted by McDonnell Douglas Aircraft Company are reported here because this information is available to the author and because these programs cover a wide variety of structures which can illustrate the potential applications of this material to the space shuttle.

6.6.1 Design, Fabrication, and Test of an Aerospace Plane Beryllium Wing-Box

Two wing boxes, each 48 inches long, 25 inches wide and 6 to 8 inches deep were fabricated and tested. The program demonstrated the feasibility of complex aerospace structural components of beryllium and the predictability of its strength level.

6.6.2 Design, Fabrication, and Testing of F-4 Beryllium Rudder

A beryllium rudder made for ground testing weighed 37.59 lbs compared to 63.03 lbs for a production aluminum rudder. These two structural components were completely interchangeable. A beryllium rudder used for flight testing was identical with the ground test item with the exception of an additional corrosion protection system. No serious damage was detected after 53 hours of flight time. As of August 20, 1969, a total flight time of 100.5 hours had been accumulated.

6.6.3 Damage Tolerance of Beryllium Structure

The test results of this program showed that the damage tolerance of beryllium panels could be increased by incorporating design features limiting the growth of cracks caused by damages or local imperfections. An ingenious design could preclude catastrophic failure of the structure.

6.6.4 Beryllium Brake Programs

Structural beryllium brakes flight tested on F-4 aircraft provided a weight saving of 49 lbs per aircraft or 23.5% of the original brake. The wear life of the beryllium brakes were at least as good as the steel ones. The cost of the steel brake was about $1275 while the cost of beryllium brake was $8000. The beryllium brake was found prone to damage during maintenance, and corrosion of the brazed beryllium might have been the cause of some failures. In another program for the A-3 aircraft, aircooled beryllium heat sink wheel brakes provided a 19% weight saving.

6.6.5 Beryllium Shingles of Mercury and Gemini Spacecrafts

Beryllium was selected for external heat protection on the upper cylindrical section of Mercury and Gemini spacecrafts. These heat shields uniformly dissipated the heat pulse caused by impingement of the corner shock wave reattachment. The 12 shingles for each Mercury spacecraft were manufactured from S-200-A hot pressed block. The 0.23 inch thickness of the shingle was required for heat sink while a maximum temperature of 1300°F was reached during reentry. The 24 shingles for each Gemini spacecraft were manufactured from cross-rolled beryllium plate and had a thickness varying from 0.07 inches to 0.28 inches, also dictated by the heat sink requirement.

6.6.6 Beryllium Frames

A beryllium structural ring frame segment made up as a I beam with beryllium caps and aluminum shear webs joined by mechanical fasteners was designed for a manned spacecraft. Here beryllium was chosen to meet the limited space available for frame depth while providing the high stiffness required. For these requirements aluminum or steel alloy designs were impossible or weightwise impractical.

7.0 POTENTIAL STRUCTURAL APPLICATIONS

Experience has indicated that beryllium can provide substantial benefit in a variety of applications when properly designed into a structure with due regard to its limitations. There are a number of potential applications for which beryllium can be expected to save weight reliably and, in some cases, cost-effectively.

Beryllium, possessing a high specific modulus, is particularly suitable for structures which are buckling critical, deflection limited, or designed for a high natural frequency. Due to its unique thermal properties beryllium can be used advantageously for structures which are thermal conduction controlled or thermal expansion sensitive. It is also an ideal choice for non-structural components or lightly loaded structures which can take full advantage of its high-stiffness, high temperature resistant capability, high specific heat, or high thermal conductivity.

7.1 Structural Components[16,20]

It is well recognized that beryllium is an attractive construction material for the following structural elements:

1. Cylindrical Column

   For slender compression elements such as actuator linkages and compression members of a truss, the theoretical weight of a beryllium member could be as low as 1/6 the weight of an aluminum or titanium member. Any cylindrical tubular structure under axial compressive load can take full advantage of the high specific modulus of beryllium. Furthermore, the high stiffness of beryllium permits increased accuracy of control when it is used for structures of guidance and control systems.

2. Cantilever Beam

   Substantial weight savings can be achieved when beryllium is used for large lightweight cantilever-beam type of structure such as a solar array. Its high stiffness can limit the deflection and the vibration of the structure. The high thermal conductivity can reduce the thermal gradient, thus alleviating thermally induced stresses. Beryllium is therefore attractive for structures exposed to temperature extremes or high temperature gradients. A Boeing study showed that for large, folding solar arrays with an output exceeding 20 watts per pound of structure, beryllium is the only satisfactory material currently available.

3. Compression Panels

   Thin panels under inplane compressive loading are also attractive candidates for beryllium application. The weight saving potential is equally impressive as for columns and cantilever beams. In the McDonnell Douglas F-4C rudder program discussed earlier, the beryllium rudder assembly was 46% lighter than the production aluminum design while torsional and bending stiffness of the former increased by 500% and 150%, respectively.

4. Panels Subjected to Flutter

Due to its extremely high specific modulus, beryllium is attractive for use in structural components subjected to flutter or buffeting. It was estimated that for a given mach number, dynamic pressure and panel size, the thickness of a beryllium panel required to prevent flutter is 60% that of an aluminum panel and has a weight about 40% that of aluminum.

Beryllium can also be applied advantageously to many other structural elements, although the weight savings may not be as large as those items discussed.

7.2 Space Shuttle Application[21,22]

A preliminary study on structural applications of beryllium for a space shuttle orbiter was conducted by Lockheed Missiles and Space Company. Weight estimates made on beryllium body structure (shell and frames), aerodynamic surfaces (fins, rudders and flaps) and thermal protection systems showed significant weight savings over equivalent aluminum or titanium structures. For a compression line load of 2000 psi the fuselage structure using beryllium was found to be one pound lighter than the aluminum structure for each square foot of wetted area, and this weight difference would be insensitive to variations of structural configuration. For aerodynamic surfaces the beryllium structure (about 3.0 lbs/ft^2) would be as much as 2.4 lb/ft^2 lighter than the aluminum design with heat shields. In the case of the thermal protection system, use of beryllium instead of titanium resulted in a weight saving of 0.75 lb/ft^2. By using beryllium in these three structural areas a total weight saving as much as 30,000 lbs could be achieved for an orbiter.

In a more recent report Lockheed claimed that by redesigning the orbiter using beryllium for primary structures, the size of the vehicle would be reduced significantly. As much as 40%, or more than 70,000 lbs of the orbiter dry weight could be saved as compared with an aluminum/titanium design. The total system launch weight of a two stage fully reusable vehicle could be reduced from 3.5 million lbs to 2.5 million lbs.

Unfortunately many of the design and fabrication problems associated with beryllium structures were not elaborated in the above mentioned reports, and a direct tradeoff between beryllium structures and those of advanced composite materials has not been made. Nevertheless, the weight saving potential of beryllium has been demonstrated.

8.0 CURRENT R&D PROGRAMS[23]

Due to overall cutback of R&D funds, government sponsored activities of beryllium technology have been decreasing steadily. On the other hand, the R&D programs initiated by beryllium producers have increased somewhat. It was estimated that beryllium producers are currently spending about 3 million dollars per year on R&D. Most of the current programs are directed toward the improvement of manufacturing techniques, improvement of fabricability, and cost reduction as well as the definition of structural applications. Very few are devoted to basic understanding of beryllium material which is felt to be necessary to form a basis for long term product improvement. Important current programs are listed in Table 7.

9.0 BERYLLIUM VERSUS ADVANCED COMPOSITES[4]

The technology of advanced composites has been advancing so rapidly that many aerospace engineers and managers have come to hinge their hopes for structural weight reduction on the application of such materials as boron/epoxy, graphite/epoxy, or boron/aluminum. The future of beryllium as a lightweight structural material, then, will inevitably depend to a great extent on its competitive position with advanced composites. As mentioned earlier, no direct tradeoff study on structural design using beryllium versus advanced composites was found in the literature. However, a qualitative comparison based on material properties is in order.

Advantages of beryllium:

1. High specific modulus
2. High temperature capability and thermal conductivity
3. A homogeneous and more or less isotropic material
4. Low fabrication cost for many applications, particularly for structures with joints and cutouts.

TABLE 7 - CURRENT BERYLLIUM R&D PROGRAMS

PRIMARY GOAL	PROGRAMS	SPONSOR	CONTRACTOR(S)
IMPROVEMENT OF MANUFAC-TURING TECHNIQUE	1. EXTENSION OF HOT-ISOSTATIC-PRESSING TECHNOLOGY TO FABRICATE THIN-WALLED SHAPES	MANUFACTURING TECHNOLOGY DIV., WRIGHT-PATTERSON AIR FORCE BASE	BATELLE MEMORIAL INSTITUTE
	2. PRODUCTION OF VERY FINE BERYLLIUM POWDERS BY THE AMELGAM PROCESS	NASA	GENERAL ASTROMETALS
	3. DEVELOPMENT OF A METHOD FOR THE PRODUCTION OF BARE EXTRUSION	BRUSH BERYLLIUM	
	4. IMPROVEMENT OF INGOT SHEET BY DEVELOPING BARE ROLLING TECHNIQUE	KAWECKI BERYLCO INDUSTRIES (KBI)	
	5. PROCESSING CONTROL OF THE POWDER METALLURGY PRODUCTS	KBI, BRUSH AND GENERAL ASTRO-METALS	
IMPROVEMENT OF PRODUCT FABRICABILITY	1. SOLID-STATE DIFFUSION BONDING WROUGHT PRODUCT	AIR FORCE MATER-IALS LABORATORY (AFML)	BOEING AND BATTELLE
	2. FABRICATION OF POROUS BERYLLIUM STRUCTURES	AFML	MCDONNELL-DOUGLAS AND BRUSH BERYLLIUM
	3. EVALUATION OF A NEW DRILL DESIGN FOR HOLE ALIGNMENT	BRUSH BERYLLIUM	
	4. HOT-ISOSTATIC-PRESSING PROCESS TO PRODUCE LARGE NEARLY NET SHAPES	GENERAL ASTRO-METALS	
	5. SHEAR FORMING OF S-120 BERYLLIUM INTO CONICAL AND OTHER SHAPES	SANDIA CORPORA-TION	PHILCO-FORD

TABLE 7 - (CONTINUED)

PRIMARY GOAL	PROGRAMS	SPONSOR	CONTRACTOR
IMPROVEMENT OF MATERIAL PROPERTIES	1. EXPERIMENTAL STUDY OF THE EFFECTS OF GRAIN SIZE, PREFERRED ORIENTATION AND OXIDE CONTENTS ON THE TENSION, TORSIONAL AND BIAXIAL STRAIN PROPERTIES	AFML	SOUTHWEST RESEARCH INSTITUTE
	2. DEVELOPMENT OF A NEW LOW-ALLOY ADDITION SHEET WITH BETTER HANDLING CHARACTERISTICS AND FRACTURE-TOUGHNESS PROPERTIES	KBI	
	3. IMPROVED MATERIAL FOR BRAKE APPLICATION	BRUSH BERYLLIUM	
	4. CHARACTERIZATION OF A NEW POWDER-METALLURGY SHEET	KBI	
IMPROVEMENT OF SIZE AND COST OF BERYLLIUM PRODUCTS	1. PRODUCTION OF SMALL-DIAMETER WIRE BY HYDRAW PROCESS	MANUFACTURING TECHNOLOGY DIR. WRIGHT-PATTERSON AIR FORCE BASE	
	2. APPLICATION OF ISOPRESSING AND SINTERING AS A PRIMARY CONSOLIDATION STEP TO PRODUCE CHEAPER BLANKS AND PROVIDES IN-PROCESS CONTROL	KBI & BRUSH BERYLLIUM	
STRUCTURAL APPLICATION	1. COST-EFFECTIVE STUDY ON BERYLLIUM STRUCTURES FOR ADVANCED AIRCRAFT	AIR FORCE FLIGHT DYNAMICS LABORATORY (AFFDL)	MCDONNELL-DOUGLAS
	2. DEVELOPMENT OF DAMAGE TOLERANT BERYLLIUM STRUCTURES	AFFDL	NORTH AMERICAN ROCKWELL
	3. BERYLLIUM STRUCTURES FOR THE SPACE SHUTTLE	LOCKHEED MISSILES AND SPACE COMPANY	

Advantages of advanced composites:

1. High specific strength
2. Superior fracture characteristics
3. Low material cost (in certain cases)

Probably the most important factor unfavorable to beryllium is the extensive research and development program on advanced composites currently underway. The progress to be made in the near future on the improvement of material properties, fabrication process and cost reduction for advanced composites would conceivably be faster than for beryllium. However, at the present state of technology beryllium may have fabrication and weight advantages over advanced composites in many applications.

10.0 ASSESSMENT OF CURRENT TECHNOLOGY AND RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

Beryllium is a unique metallic material. The most valuable asset of beryllium for structural application is its unusually high modulus, high thermal conductivity and low weight. These properties make beryllium competitive weightwise with other advanced engineering materials. Its main drawbacks are brittleness, low strength and high material cost.

The brittleness makes beryllium difficult to fabricate relative to conventional metals. In the past few years, impressive progress has been made in improving the ductility of beryllium. Currently available raw material products are generally considered manageable and easier to work with then are many of the advanced composite materials, particularly for structural elements with joints and cutouts. The material cost is high but, in comparison with advanced composites, the overall cost of installed structure may be lower in certain applications. The relatively low tensile strength often cancels the advantage of its unusually high stiffness. Nevertheless, beryllium may still be the best choice for structural elements which are buckling critical, deflection limited, or designed for a high natural frequency. It is particularly suited for lightly loaded structures vulnerable to instability failure and for non-structural components requiring its unique thermal properties.

The future of beryllium as a lightweight engineering material for aerospace structures appears to be overshadowed by the rapid development of advanced composites. The very limited research activity on beryllium is currently overwhelmed by the extensive programs devoted to the composites. It is difficult to foresee beryllium application in large quantity for primary aerospace structures in a long run under the challenge of advanced composites. This trend is particularly perceivable in view of the fact that most of the current beryllium research and development programs are engineering problem oriented, which would not permit a rapid accumulation of basic material knowledge needed for long term product improvement.

However, at present, many design and fabrication difficulties exist in structural application of advanced composites. For near term space programs such as the Space Shuttle, many structural elements may be identified as best suited for beryllium application. For some structures beryllium may be selected as an alternative or backup material. It was noted in a previous Bellcomm memorandum[24] that very little effort has been devoted to beryllium in the current space shuttle structures and materials technology program. Since weight reduction will be a primary concern in the Space Shuttle development, it is felt that a limited investment on beryllium technology to boost the soft areas of current industry activities and to critically evaluate beryllium as a candidate material for primary as well as secondary structures would be a worthwhile effort to ensure a reliable material source for a lightweight vehicle. To this end the following study tasks are suggested:

1. Generation and evaluation of material property data at low temperatures
2. Effect of meteoroid impact, particularly at low temperatures
3. Fracture control of beryllium structures
4. Coordination and cooperation with beryllium industry and other government agencies to generate an engineering design handbook for beryllium structures
5. Identification of complex Space Shuttle structural components involving joints and cutouts for which beryllium can out-perform advanced composites and other engineering materials.

6. Identification of flutter critical heat shield panels in a space shuttle vehicle for which beryllium can best be applied

7. Identification of design and fabrication problems and difficulties of beryllium primary structures for a space shuttle

8. Tradeoff between selected structural elements using beryllium and advanced composites.

1013-CCO-klm

C. C. Ong

C. C. Ong

REFERENCES

1. King, B., "Discussion of Certain Aspects of the Beryllium State-of-the-Art," Presented at the Beryllium Conference, Washington, D. C., March 23-25, 1970.

2. Lowe, J. N., "Beryllium Technology," J. of the British Interplanetary Society, Vol. 22, 1969.

3. "Beryllium Properties and Products," Kawecki Berylco Industries, Inc., File Number 302 00-PD 1.

4. Kiersarsky, A. S., and C. C. Ong, "Advanced Composites for Aerospace Structures," Bellcomm Memorandum for File, May 19, 1970.

5. Lidman, W. G., and F. K. Young, "Hot Isostatic Pressing of Beryllium," Presented at the Beryllium Conference, Washington, D. C., March 23-25, 1970.

6. Richards, D. J., "Improved Beryllium Mill Products," Presented at the Beryllium Conference, Washington, D. C., March 23-25, 1970.

7. Snider, R. E., and J. F. Kahles, "Machining Data for Beryllium Metal," Rept. AFMDC 66-3, Air Force Machinability Data Center, Cincinnati, Ohio, June 1966.

8. Kelly, R. N., "Beryllium Structures," Space/Aeronautics, July 1964.

9. Williams, R. F., and S. E. Ingels, "The Fabrication of Beryllium Volume VI: Joining Techniques for Beryllium Alloys," NASA-TM-X-53433, July 1966.

10. Long, J. V., and G. D. Cremer, "Beryllium: Brazing and Welding," ASE Paper No. 680651, Presented at Aeronautic and Space Engineering and Manufacturing Meeting, October 7-11, 1968.

11. Ingels, S. E., "Ductility of Cross-rolled Beryllium Sheet Barrier or Challenge," Presented at Society of Automotive Engineers, National Aeronautic Meeting, New York, April 25-28, 1966. (Paper 660291)

12. Rebholz, M. J. "Application of Beryllium on the Agena" J. Spacecraft - Vol. 3 No. 5, May, 1966.

13. Ingels, S. E. "Beryllium Structures - Lockheed Agena Spacecraft" Presented at Beryllium Conference, Washington, D.C., March 23-25, 1970.

14. Armelin, J. P., Broding, W. C. and King, D. B., "The Minuteman Beryllium Spacer," presented at the Beryllium Conference, Washington, D.C., March 23-25, 1970.

15. Terry, E. L. and Ely, W. E., "Application of Beryllium Brake Disks on the Lockheed C-5A Aircraft", presented at Beryllium Conference, Washington, D.C., March 23-25, 1970.

16. Bleymaier, J. S. and Weiss, M., "Systems Considerations for Aerospace Beryllium Applications", presented at Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, California, October 7-11, 1968.

17. Switz, R. J. "The use of Beryllium in Large Spacecraft Structural Assemblies", presented at Beryllium conference, Washington, D.C., March 23-25, 1970.

18. Information furnished by Kawecki: Berylco Industries, Inc., October, 1970.

19. Koch, L. C., "Abstracts of Design and Development of Beryllium Aircraft Structures and Design Concepts for Damage Tolerant Beryllium Structures," Presented at Beryllium Conference, Washington, D. C., March 23-25, 1970.

20. Barnett, F. E. and Finn, J. M. and Koch, L. C., "Beryllium Structures for Aircraft", presented at Aeronautical Space Engineering and Manufacturing Meeting, Los Angeles, California, October 3-7, 1966.

21. Harvey, T. J. "Application of Beryllium In Space Shuttle," Presented at Beryllium Conference, Washington, D.C., March 23-25, 1970.

22. "Study of Materials Selection for Space Shuttle Orbiter Structure and TPS". Engineering Memorandum L2-01-01-M2-1 Lockheed Missiles and Space Company, August 7, 1970.

23. Hanes, H. D. "Summary of current Beryllium R&D Programs" presented at Beryllium Conference, Washington, D.C., March 23-25, 1970.

24. Ong, C. C., "Space Shuttle Structures and Materials Working Group Meeting - MSC, October 22-23, 1970", Bellcomm Memorandum for File, November 10, 1970.